STRENGTHENING AND SUSCEPTIBILITY TO ANNEALING OF COPPER AND ALUMINUM

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Abstract

The abnormal prices of copper and aluminum over the last decade have led to increasing substitution of copper with aluminum. This is mainly possible due to the favorable relation of the strength properties of aluminum to its density with respect to copper. An aluminum conductor with the same length and the same resistance has twice the weight of a copper conductor. The main technological problem of substituting copper with aluminum lies in the technology of drawing small diameter aluminum wires and their annealing on-line. In recent years, this problem has been effectively solved by introducing dedicated aluminum alloy grades and a new generation of rod breakdown machines and multiwire machines that allow drawing aluminum using emulsions with simultaneous annealing of online wires in a way similar to annealing copper wires. Due to the high stacking fault energy of aluminum in relation to that of copper, the aluminum alloy is characterized by a recovered structure, which translates into low susceptibility of the aluminum wires to annealing. This problem is not observed with copper wires. The article includes the results of studies of the process of strengthening Cu-ETP copper wire rods and EN AW-1350 aluminum wire rods, and the annealing characteristics (softening curve) observed during the hour-long annealing process. The structures of wires after drawing and after annealing. The analysis of the studies shows that the temperature of recrystallization of aluminum wires is about 200 ° C higher than that of copper wires of the same deformation degree. There was a significantly different recrystallization kinetics of the studied wires (different angle of slope of the UTS = f (T) characteristic), which translates into the need for other current settings in the annealing line in production lines.

Keywords: Copper wires, aluminum wires, EN AW-1350, Cu-ETP, annealing, recrystallization, strain hardening, softening curve

1. RAW MATERIALS FOR DRAWING PROCESS OF COPPER AND ALUMINUM WIRES

Modern processing technologies for copper and aluminum wire rolling aim to maximize the efficiency and reliability of the drawing process. This imposes a new set of requirements for the batch material to be drawn within the range of recrystallization susceptibility that occurs in the drawing lines in less than a fraction of a second. In turn the properties of the wire rod are limited by the chemical composition and parameters of the continuous casting and rolling process.

The quality of copper wire used for electrical purposes in accordance with current standards and world trends is currently evaluated by manufacturers for its electrical conductivity and susceptibility to annealing. While the first of the properties uniquely evaluates the chemical quality of the cathode from which the wire is made, the second material property is a function of both the chemical composition and the material's condition. According to the ideological technological diagram of the manufacture of copper wires shown in **Figure 1**, we note that in the whole production cycle there can be three links in which the chemical composition and the material's condition are shaped.

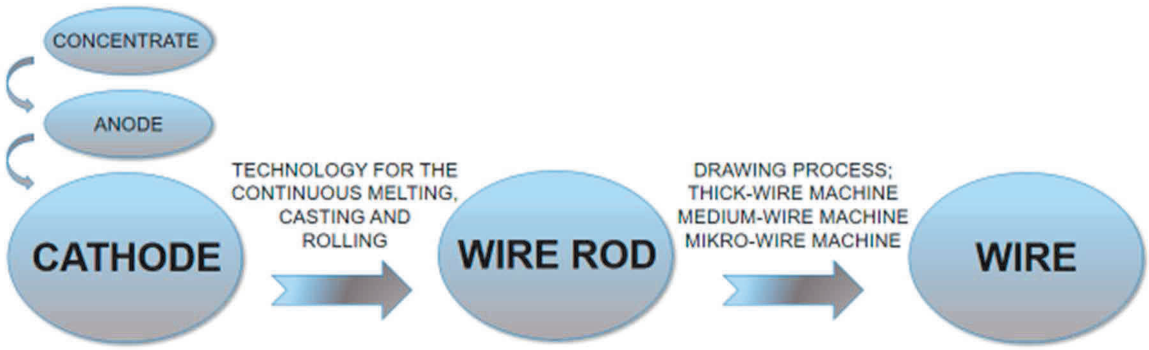


Figure 1 Ideogram for the production of copper wire

In the first stage, the final total content of the pollutant elements, which is the consequence of the type of copper ore or concentrates used for the production of the cathode, is determined. The ROLLING stage is a part of the production cycle, which involves the last metallurgical interference in the copper/aluminum chemistry, and the formation of the condition of the batch material for further processing, through the casting process followed by hot rolling. Thus, the above step combines the two most important operations in terms of ensuring the quality of the final product: the chemical composition and the condition of the batch material. The last stage of production consists of a multi-step drawing process combined with multiple annealing of the material, resulting in the final product. While analyzing the above steps in terms of the mechanisms involved, three processes can be distinguished which, with the assumed chemical composition, determine the possibility of obtaining the right properties of the final product. These are: deformation, dynamic recrystallization and static recrystallization [1-4].

Copper rods with very good annealing capability should ensure the possibility of full recrystallization of the wires during the drawing process on multi-speed machines. Manufacturers currently use drawing speeds of 30 m/s. This means that we are dealing with increasingly less comfortable conditions in the annealing process on the line, which must be implemented in a fraction of a second. Thus, the ideal material in terms of annealing susceptibility should be characterized by an annealing kinetics that will allow the material to be softened from the hard state as soon as possible. This sets new requirements for wire rod manufacturers and at the same time requires a detailed revision of the chemical composition already at the stage of requirements addressed to the cathode manufacturers, i.e. producers of wire rod material.

On the other hand, in the case of aluminum rods, the manufacturers firstly require adequate electrical conductivity, tensile strength and elongation. So far, contrary to copper rods, the standards do not require aluminum rods to guarantee adequate annealing. The above fact is mainly due to the type of application. In the case of copper wires, most of them are in soft temper and are used in Class 5 and 6 (IEC 228). Aluminum wires, on the other hand, are mainly used as class 2 wires and are usually in a hardened condition. However, for several years now, economic conditions have led to the substitution of copper with aluminum in grades 5 and 6. This fact entailed a market demand for aluminum wires for Class 5 cables. Hence, the answer to the question whether aluminum rods meet the new requirements that concern the production of small diameter soft wires is interesting.

2. PURPOSE OF THE PAPER AND EXPERIMENTAL RESEARCH PROGRAM

The aim of the paper is:

- to assess the hardening susceptibility in the drawing process of aluminum and copper rods and
- to assess the annealing susceptibility of the wires produced from said rods.

The program of experimental research involved research on the drawing process of copper and aluminum rods. In both cases, the drawing process was carried out to obtain a strain hardening of max. about 90 %.

Table 1 Diameters of EN AW-1350 and Cu-ETP wires and the test wires and their corresponding strain hardening

EN AW-1350				Cu-ETP			
Diameter (mm)	Strain (%)	Elongation factor (-)	True strain (-)	Diameter (mm)	Strain (%)	Elongation factor (-)	True strain (-)
9.5	0.0	1.00	0.00	8.0	0.0	1.00	0.00
8.7	16.1	1.19	0.18	7.0	23.4	1.31	0.27
6.0	60.1	2.51	0.92	5.5	52.7	2.12	0.75
4.5	77.6	4.46	1.49	4.5	68.4	3.16	1.15
2.9	90.7	10.73	2.37	2.5	90.2	10.24	2.33

The wires produced with different strain hardening were further subjected to annealing at different temperatures to evaluate the effect of the strain hardening on the recrystallization temperature. Aluminum wires were heated in the temperature range of 200-450 ° C and Cu-ETP wires in the temperature range of 180-600 ° C.

3. STUDY RESULTS AND ANALYSIS

On the basis of the research, reinforcement curves for wires made of copper and aluminum rods were first developed. **Figures 2** and **3** show graphs representing the strength curves of the studied wires.

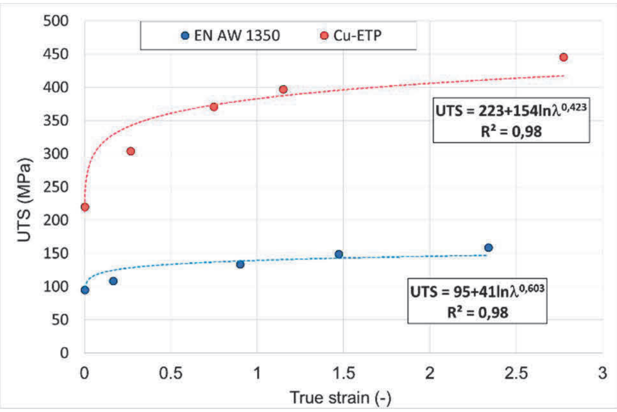


Figure 2 Comparison of the conventional yield point as a function of true strain of Cu-ETP and EN AW-1350 wires

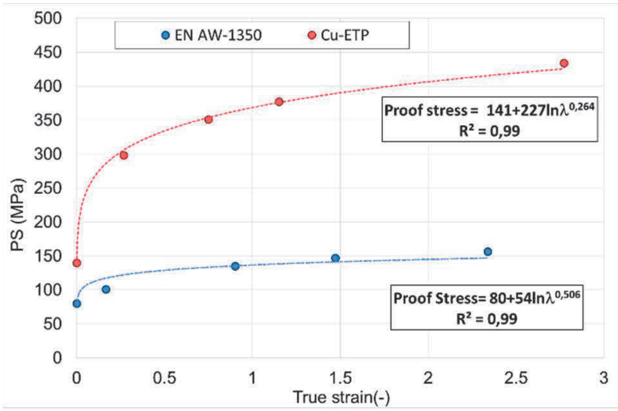


Figure 3 Comparison of the tensile strength as a function of true strain of Cu-ETP and EN AW-1350 wires

Based on the above graphs, it can be said that the same strain hardening results in a double increase in the strength properties of copper wires compared to aluminum wires. It can be noted that in the case of aluminum wires, the increase of the yield strength upon 90 % strain is about 100 %, while in the case of copper wires - 200 %. The relation between strength properties and strain hardening is described by the mathematical equation:

$UTS = UTS_{wirerod} + k(ln\lambda)^n$ and

$Proof\ Stress = Proof\ Stress_{\ wirerod} + k(ln\lambda)^n$

Table 2 Parameters of strain hardening curve of Cu-ETP and EN AW-1350

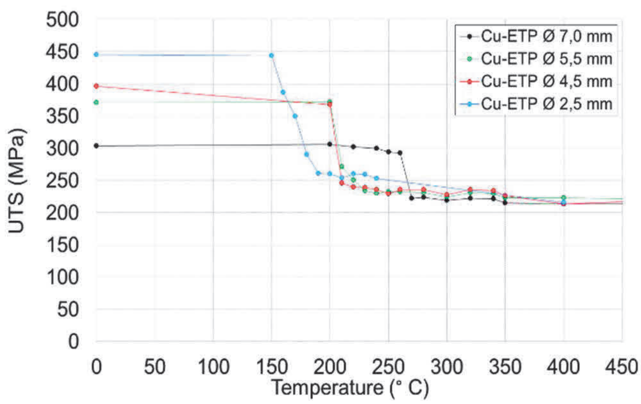
Material	UTS		Proof Stress	
	k	n	k	n
Cu-ETP	154	0.423	227	0.264
EN AW-1350	41	0.603	54	0.506

An analysis of the coefficients in the hardening curve equation (see **Table 2**) showed that the linear coefficients for aluminum are almost three times lower, while the coefficient of the power factor is twice as high. In the next stage of research, the aluminum and copper wires were tested for annealing susceptibility. The purpose of the study was to evaluate the effect of deformation on the recrystallization temperature of copper and aluminum. **Table 3** shows the mechanical properties of wires before the annealing process

Table 3 Mechanical properties of wires in grade Cu-ETP and EN AW-1350

EN AW-1350				Cu-ETP			
Diameter (mm)	UTS (MPa)	Proof Stress (MPa)	Elongation A_{250} (%)	Diameter (mm)	UTS (MPa)	Proof stress (MPa)	Elongation A_{250} (%)
9.5	95	72	17.25	8.0	220	140	40
8.7	108	133	4.94	7.0	304	298	4.73
6.0	134	140	0.85	5.5	371	350	3.23
4.5	150	147	1.15	4.5	397	378	2.50
2.9	160	158	1.80	2.5	446	434	1.03

Figures 4 - 7 show the softness curves of the examined copper and aluminium wires, in which the dependence of the change in tensile strength is shown in **Figure 4** - the proof stress curve and in **Figure 5**.



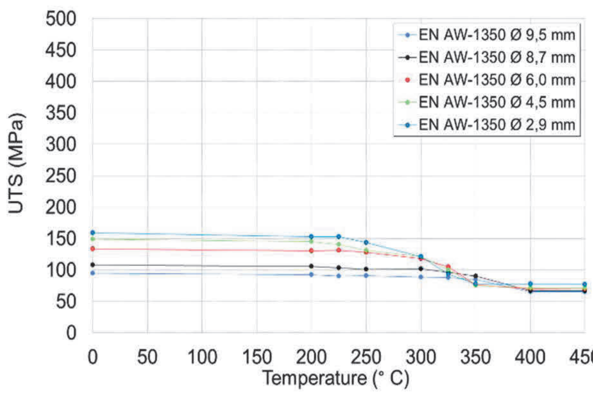


Figure 4 Relationship between tensile strength and annealing temperature of copper wires (left) and aluminum wires (right)

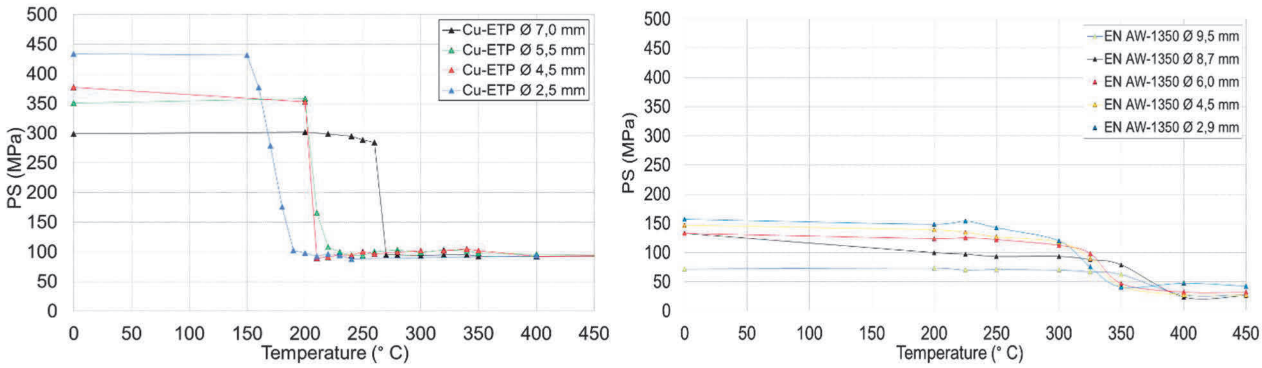


Figure 5 Relationship between proof stress and annealing temperature of copper wires (left) and aluminum wires (right)

Based on the above characteristics, the dependence was developed of the influence of the deformation strengthening on the recrystallization temperature of the studied wires.

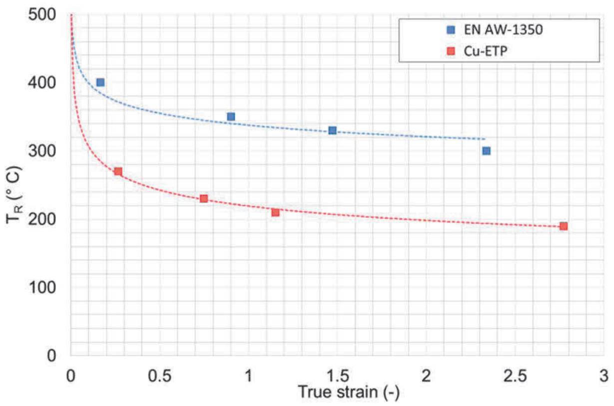


Figure 6 Relationship between recrystallization temperature and strain hardening of Cu-ETP and EN AW-1350

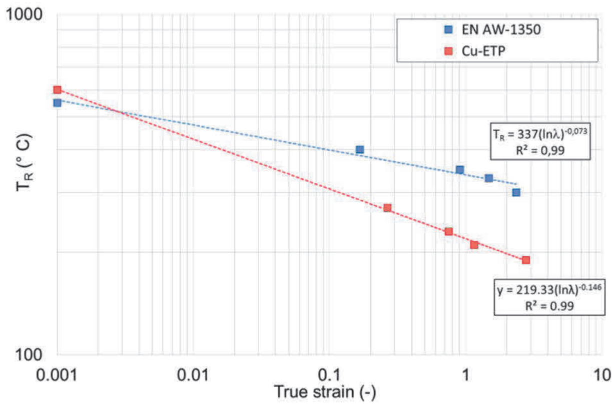


Figure 7 Relationship between recrystallization temperature and strain hardening of Cu-ETP and EN AW-1350 (logarithmic system)

Based on **Figures 6** and **7**, showing the graphs illustrating the effect of deformation on the change in the recrystallization temperatures of Cu-ETP and EN AW-1350 mathematical models have been determined to describe said dependence. In both cases, this relation has been described as an exponential function in the form:

$T_R = a \cdot ln\lambda^b$, where

T_R - recrystallization temperature

lnλ - true deformation

a, b - material constants

The **Table 3** shows the values of parameters a and b of the analyzed materials.

Table 3 Parameters of the function describing the effect of deformation on the recrystallization temperature

Material	a	b
Cu-ETP	218	-0.147
EN AW-1350	338	-0.073

Based on the analysis of the above mathematical models of the effect of the deformation on the change in the recrystallization temperature of the materials tested, it can be stated that the power factor coefficient b for copper is twice that of aluminum. In turn, the coefficient a is higher for aluminum. Thus, the effect of strain hardening in the case of copper results in a significant decrease in the recrystallization temperature, as compared to aluminum. The cause of the above situation results primarily from the diversity of the input materials. Both batch materials were formed in a continuous casting and rolling line. **Figure 8** shows the macrostructure images of the ingots produced in the Hazzalett machine (copper) and the Properzi wheel (aluminum). In both cases we are dealing with a typical foundry structure with clearly marked crystallization interfaces. As a result of the hot rolling process, the so-called wire rod is obtained, whose macrostructure is shown in **Figure 10**. Let's note that copper rods are characterized by a fine grain structure - grain size does not exceed 30 µm (see **Figure 9**), which is a result of dynamic recrystallization. In turn, aluminum rod during the rolling process did not get a fine grained structure like copper rod. In this case, there was no dynamic recrystallization process, with the curing process taking place instead. Hence the differentiation of the two input materials for the drawing process results [5].

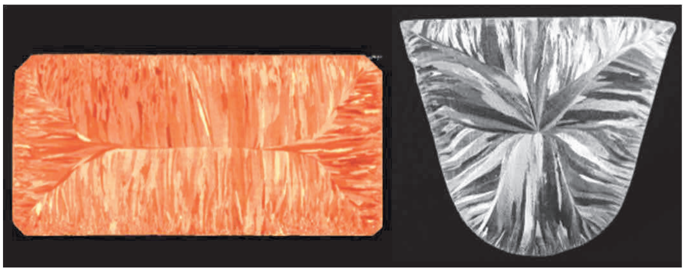


Figure 8 Ingot Cu-ETP, EN AW-1350

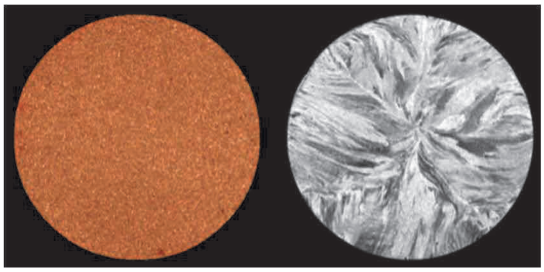


Figure 9 Wire rod Cu-ETP - 8.0 mm, EN AW-1350 9.5 mm

The **Figures 10** and **11** shows the structure of copper and aluminum wires after the annealing process. We may note that the variation in the structure of the raw material directly translates into the differentiation of the structure after the annealing of the wires produced therefrom.

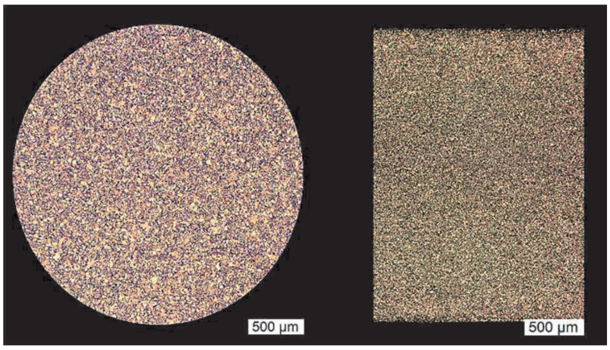


Figure 10 Microstructure of Cu-ETP wire with a diameter of 2.00 mm in annealed temper

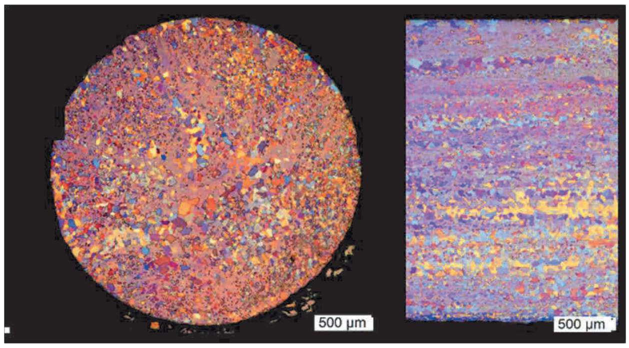


Figure 11 Microstructure of EN AW-1350 wire with a diameter of 3.0 mm in annealed temper

4. CONCLUSION

Based on the results of the research, the following conclusions were made:

1) As a result of the drawing process of aluminum and copper rods, it was found that in the case of copper rods, there was over two times increase in strength properties compared to aluminum rods. This is due to the higher strength properties of copper rod compared to aluminum rod.

2) The recrystallization temperature of aluminum wires is about 200 ° C higher than that of copper wires with the same strain hardening. There was a significantly different recrystallization kinetics in the studied wires (different tilt angle of characteristic UTS = f(T)), which translates into the need for other current settings for annealing in drawing lines).

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